Hyperloop Storage Energy Options: Lithium Ion Batteries, LightSail Technology, and Nuclear Batteries.*

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Abstract

Technical evaluation of energy storage options for the Hyperloop transportation system.

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Abstract

The following technical report investigates and evaluates viable energy storage options for Elon Musk's Hyperloop system, a proposed alternative method of transit for the California high-speed bullet train. These storage options include LightSail technology, Lithium ion batteries, and a radioactive power system called Advanced Stirling Radioisotope Generator (ASRG). After creating a Pugh Matrix and evaluating these technologies, the most viable and feasible energy storage option available to the Hyperloop is the Li-ion battery, which provides advantages in size, efficiency, energy storage capacity, and other promising characteristics.

Introduction

A statewide mass transit system that is more efficient than flying or driving would enhance the lives of the thousands of people that travel across California as part of their daily routine. The state of California has approved the development of a high-speed bullet train in an attempt to accomplish the goal of establishing an innovative statewide mass transit. However, because this train will be slow and costly, Elon Musk, founder and CEO of SpaceX, believes that California can provide a much better alternative than the high-speed bullet train. His answer is an innovation of his own: the Hyperloop Alpha. The Hyperloop consists of low-pressure tubes with capsules that are transported at both high and low speeds. This system ideally provides a safer, faster, and less costly mode of transportation between Los Angeles and San Francisco, California in only thirty-five minutes. However, a viable energy storage option for these capsules has not yet been found since the battery must power the capsule throughout the entirety of the travel time. This report aims to solve the energy dilemma by providing a recommendation for the Hyperloop Alpha battery after an evaluation and detailed analysis of different energy storage options.

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1 Background

LightSail
LightSail is a groundbreaking new energy storage technology with the potential to power the Hyperloop pods in a clean, efficient, and safe fashion. LightSail takes advantage of isothermal compression and expansion of air to improve upon the old and outdated method of electricity generation (1). The traditional method of electricity generation involves using solar panels or wind turbines to turn a motor that compresses air in a large tank. The created air pressure is then converted into power that is used to drive a generator (2,3). LightSail upgrades this traditional method by spraying water mist into the air as it is compressed in order to capture heat energy generated by the air compression (2). After spraying, the compressed air is moved into a storage tank, and the heat captured by the water is stored as well. Finally, during expansion, the heated water is sprayed back into the expanding air (4). This water assists the expansion and improves upon the traditional electricity generation process. As a result, LightSail has the potential to drastically improve grid efficiency since energy is often lost during expansion.
Lithium-Ion Battery
The Li-ion battery is one of the most widely acknowledged energy storage used technologies today. Li-ion battery cells are pressurized, with a metal sheet holding together three components: a positive electrode, negative electrode, and separator. The main topic of discussion in the Li-ion battery research is of the components that make up the battery cells. Much research is being conducted to determine which electrodes and separators should be used to perform at the highest electrical potential possible. For the sake of this discussion though, the following electrodes will be taken into consideration for the battery storage. The positive electrode is made of olivine-type lithium iron phosphate ($LiFePO4$) cathode (5). The negative electrode is made of carbon (6). When the battery charges, ions of lithium move through the electrolyte from the positive electrode to the negative electrode and attach to the carbon.

During discharge, the lithium ions move back to the $LiFePO4$ from the carbon. The movement of these lithium ions happens at a fairly high voltage, so each cell produces approximately 3.7 volts for a typical Li-ion battery (7) One key benefits of the battery pack is that it is not harmed by partial discharge of the electrodes. Additionally, the battery still functions at the same capacity after re-charge.
ASRG
NASA uses numerous radioisotope power systems to supply the energy and heat for a wide variety of space missions (8). One of these systems, an Advanced Stirling Radioisotope Generator (ASRG), produces electricity by a triple energy transformation. First, the two Stirling converters located inside the ASRG transform the extracted heat from the radioactive decay of Plutonium-238 into high-speed kinetic motion of a piston. The Stirling converter is a thermal converter, which implies that its power output is dependent on a temperature differential. This temperature difference arises from the helium gas suspended in the piston. This gas moves rapidly from the hot end, heated by the Pu-238 decay, to the cooler end of the ASRG. Next, magnets on the piston rapidly move back and forth, oscillating through a coil of wire at a rate of about 102 cycles per second. The constant expansion and contraction of the Helium gas in the piston is what drives the magnets in the piston through the coil of wire. Lastly, following the principle of Faraday's law, the magnetized piston moving through the coil of wire generates electricity. Currently, the Department of Energy is constructing ASRGs for NASA.

2 Evaluation Criteria

Introduction and Evaluation of Criteria
The criteria for the Pugh Matrix are split into four divisions: Energy Storage and Performance, Economics, Reliability, and Safety. Each division has two subdivisions. Energy Storage and Performance contains the subdivisions of Efficiency and Feasibility. Energy Storage and Performance details how well the storage system can utilize the energy for the Hyperloop system. Efficiency refers to how much energy the system can use towards the Hyperloop versus how much is available. Feasibility concerns how easily the technology could be implemented today.

For Safety, the concerns are two-fold. First, it is important what negative effect the system could have on the environment (Eco-Friendly subgroup). More importantly, there is the Human Health concern. This subgroup deals with the possibility that any of these energy storage systems could cause negative health effects to its passengers.

For Economics, there are two subgroups: Cost and Scalability. Economics deals with the overall financial aspect of the project. Cost is simply how much money the system will cost. Scalability describes how easily the system can be implemented into the Hyperloop capsules and how much money it might take to do so.

Lastly, Reliability is how effective the system is on a daily basis. For Reliability, the subdivisions are Consistency and Durability. Consistency details how well the system can give equivalent results repeatedly. Durability goes into how the long system will last before it will have to be replaced or serviced/upgraded.

Justification of Pugh Matrix Weighting

The team assigned the Pugh Matrix criteria weightings after careful deliberation and consideration as to which aspects were most important to an effective Hyperloop design. First, ranking the four main criteria in order of importance: Energy Storage and Performance, Safety, Economics, and Reliability. Then, assigning weightings to the subdivisions of each of the criterion.

Out of the four main criteria, it was deemed Energy Storage and Performance to be the most important because some of the most prominent criticisms of the Hyperloop transportation system include its potential to be ineffective and wasteful. Thus, the technology we choose as the proposed energy storage option must be high performing and capable of storing a great deal of energy. Therefore, Energy Storage and Performance was assigned a weighting of 40%. The Feasibility subgroup received a weighting of 25% because the success and effectiveness of the energy storage system relied on its ability to be plausibly integrated into the Hyperloop system. The Efficiency subgroup was assigned a slightly lower weighting of 15%. While efficiency is an important category of the Energy Storage and Performance criterion, the design needs to be feasible before it can be judged on its efficiency.

The second most important criteria, Safety, received an overall weighting of 25% because human safety has always been an important factor in designing transportation systems. The Human Health subgroup was assigned a weighting of 20% because commuters are unwilling to use a transportation system that could endanger their lives, either by health hazards due to long-term exposure to the system or by safety hazards, such as crashes or collapses, inherent to the design. Additionally, the team accounted for the importance customers would place on environmental safety. Recognizing that human safety will always be viewed as more important than environmental friendliness, eco-friendly subgroup was assigned a 5% weighting.

The third criterion, Economics, was assigned an overall weighting of 20%, slightly less than safety. With a $10 billion plan in place for the construction of this Hyperloop transportation system, cost is not the most prohibitive criterion. Therefore, the Cost subgroup received a weighting of 10%. Additionally, the Scalability subgroup also received a weighting of 10%. While the design should, ideally, be scalable to other transportation systems, the most important goal is to create a high-performing design that is both energy-efficient and safe. Scalability is more applicable to later phases in this design project.

Lastly, the final criterion, Reliability, was assigned an overall weighting of 15%. All three designs were evaluated as relatively reliable, so the team weighed this criterion least. The Consistency subgroup was weighted as 10% because the proposed energy storage system needed to be dependable. The Durability subgroup received a 5% weighting because a long lifetime is desired; however, this subgroup was viewed as less important than Consistency.

3 Discussion

General Assumptions

Several assumptions were made to calculate values used in the following discussion. First, the compressor was assumed to be powered by a 325 kW electric motor. Elon Musk provided this value in the Hyperloop documentation. Second, it was assumed that the onboard stored energy only powers the compressor. Third, the temperature within the tube and capsule was assumed to be 25 °C, which is ambient temperature. Lastly,

Elon Musk's estimated weight and cost of the battery he proposed to power the Hyperloop was estimated to be 2,500 kg and $150,000/capsule.

LightSail

Assumptions

While performing calculations for the LightSail technology, it was assumed that all values from the LightSail technology overview on their website were relevant and appropriate to use for modeling LightSail technology on a smaller scale. Second, it was also assumed that the mechanics of LightSail were not impacted by high speed travel. Third, the proposed LightSail efficiency value was assumed to be 70%, the value provided in the LightSail patent. Additionally, it was assumed that the tube was made from a common steel alloy (priced $2.45/kg, with a density of 7.85 g/cm3.) (10,11) Moreover, it was assumed that the Hyperloop capsule operated under perfect conditions with regards to time; that is, the system completed its journey within 35 minutes. Finally, the pressure inside the tank storing the air was assumed to be 3000 psi and the ambient pressure was assumed to be 100 Pa (13).

General Calculations

Using the equation provided in the LightSail patent for storage energy density (the amount of work stored per unit volume in a storage vessel) yielded the following (12):

W/V_0 =P_a [1+(P_0/P_a)[ln(P_0/P_a)-1]]*e

Where W = stored work (in Joules), V0 = volume of storage unit (in m3), Pa = ambient pressure (in Pascal's), P0 = pressure inside the tank (in Pascal's), and e = efficiency of the system.

For the LightSail calculations, it was assumed that the system required 325 kW of power and calculated the work required for 35 minutes (or 2100 seconds) of operation (9). From these assumptions, the work required to operate the LightSail system was 682,500 kJ (see Calculation 1, Appendix).

Assuming the pressure inside the tank, P0 was 3000 psi (2.0684 x 107 Pa), the ambient pressure, Pa, was 100 Pa, and the efficiency of the system, e, was 70%, the required volume of the storage tank for the compressed air was calculated to be 4,190 L (see Calculation 2, Appendix) (1).

Energy Storage and Performance

Based on the above calculations, the LightSail would require 682,500,000 J of energy to run the pods from Los Angeles to San Francisco (assuming a 35 minute travel time). Once this amount of energy was found, the volume of the tank was calculated as 4,190 L, as seen in the above calculations. This size of tank will allow the required expansion and compression process to take place in order to supply energy to each of the capsule. In conclusion, the LightSail process will be able to store the required amount of energy and perform to expectation within the boundaries imposed by the Hyperloop pods. Thus, it received a 4 on the Pugh Matrix for Efficiency.

However, the feasibility of the LightSail technology is low because this technology is still in the development phase (13). Compared to Li-Ion and ASRGs, LightSail is still a theoretical technology that has yet to be proven on a large scale. While the projected values are promising, there are still some issues with the technology, particularly with capsule weight and scalability. Thus, the technology received a 3 in terms of Feasibility.

Safety

There are not any dangers associated with LightSail technology other than moving mechanical parts, which will not come into contact with passengers during their journey (3). Since these mechanical parts will be isolated from the passengers, there is no immediate danger associated with using LightSail technology.

Also, since the technology mainly depends on air and water to operate, there is no detriment to the environment (12). Both of these resources are renewable sources of energy, so they are both easy to obtain and have zero-impact on the environment. Thus, both subgroups (Eco-Friendly and Human Health) received scores of a 5 on the Pugh Matrix.

Economics

The minimum required wall thickness of the tube used to encapsulate the compressed air was calculated using an online calculator (14). Assuming an internal psi of 3000 psi, an inside shell radius of 0.5842 m (optimal radius for capsule to fit inside Hyperloop capsule), a maximum allowable stress value of 25,000 psi,

and a joint efficiency of 100%, the minimum required wall thickness is 0.0755 m (14,15,16). This yields an overall capsule radius of 0.6597 m.

Then, the height of the capsule required for this volume of compressed air was calculated:

V=πr^2 h=4.190 m^3=π(0.6597 m)^2 h

h=3.067 m

Next, calculating the volume of steel required to make the solid tube used to construct the metal capsule. Using an online calculator, the volume of the solid tube (assuming an inner radius of 0.5842 m, an outer radius of 0.6597 m, and a height of 3.067 m) was calculated to be 0.8967 m (3,17).

This solid tube volume was used to calculate the total cost of steel required to manufacture this tube. Assuming a density of alloy steel of 7.85 g/cm3, the mass of steel needed to construct one capsule is 7,039 kg. At a price of $2.45/kg of alloy steel, the steel required to manufacture this compressed air capsule would cost $17,246.

This cost is extremely low compared to Lithium Ion and ASRG technologies, yielding a score of 5 for the Cost subgroup on the Pugh Matrix.

However, the LightSail technology received a 3 on the Pugh Matrix for the Scalability subgroup because it is will be more difficult to implement into the Hyperloop capsules because it is unclear if the LightSail technology can be appropriate scaled down to meet the Hyperloop requirements. Since the Li-Ion requires a smaller storage capsule volume (about 0.6513 m3, compared to about 4.190 m3 for LightSail), the LightSail technology received a lower rating.

Reliability

The LightSail company guarantees that its energy storage mechanism will run for more than 20 years before having to be replaced (3). Since it lasts for this long period of time, LightSail is a durable energy storage mechanism for the pod.

During test runs, LightSail was operated for more than 500 hours without any major issues (3). Consequently, LightSail can be viewed as a consistent energy source. Therefore, both subgroups (Consistency and Durability) received scores of 5 on the Pugh Matrix.

Li-Ion Battery

Assumptions

• Hyperloop will use the largest battery size available on the market, 72V-100AH brand (18) • A combination of these batteries would be effective enough to produce the overall power needed

General Calculations

In the calculations, the team utilized a company that sells various sizes of Li-ion batteries (18). Assuming the Hyperloop will use the largest size available, the team calculated the number of these batteries that would be necessary to power the Hyperloop capsule. The assumption was made that a combination of these batteries would be effective to produce the overall power needed. Furthermore, an efficiency value of 0.8992 was used for T = 25 °C (5). It was assumed that this was an acceptable value for ambient temperature in the Hyperloop tube where the battery will reside within the capsules.

Given that 325 kW is required, this was set equal to the number of batteries times the efficiency times the product of the voltage and the current of the battery:

The most powerful battery available was the 72V-100AH brand. Using these numbers, it's found that approximately 51 of these batteries will be needed to power the capsule. A single battery was scaled up the specifications for the purpose of the power needed. Collectively, the battery system will weigh 647.73 kg and take up 0.650 cubic meters.

Lastly, each battery is available for the cost of $7,799.94 (18). Cumulatively, the total cost will be $397,796.94. However, each battery will run for approximately 2.5 years so the annual cost will be $159,118.66 (see "Economics" for specific calculations).

Energy Storage and Performance

Li batteries have great energy density and great volts/cell. They are six times as effective as normal lead-acid batteries. Furthermore, they do an efficient job of holding their charge as they lose only about five percent of their charge per month. Additionally, they can handle hundreds of charge/discharge cycles (7). They also

have a low weight to volume ratio, which is useful for the Hyperloop system in decreasing overall weight bearing and size for the capsule.

In terms of the Pugh matrix, the Li ion battery was shown to be an effective energy system with a score of 5. It has an extremely high efficiency of 0.8992 and is very feasible as these batteries are easy to obtain and implement (5).

Safety

Environmentally, Li-ion batteries received an average rating on the Pugh matrix. In fact, there is currently a patent in place for a method of effectively recycling lithium-ion batteries (systems and methods). This involves using a high-energy ball mill for recrystallizing, reordering, and reconstituting the battery material (19). While they are much more environmentally friendly than other batteries, they are far from a green energy system.

In terms of human health, they are almost always perfectly safe. The one caveat is that approximately 2-3 cells out of every million are known to burst into flames due to internal short circuits at high temperatures (7). This occurs due to the pressurized container inside the battery pack, when exposed to high temperatures. If the separator sheet (separating the positive and negative electrodes) gets punctured and the electrodes touch, the battery heats up very quickly. Given the ambient temperature of the Hyperloop capsule, this should not be a concern.

Economics

One disadvantage of lithium-ion batteries is that they are typically more expensive than other batteries. Another cost consideration is that the batteries will need to be replaced every two to three years when they expire (assuming 2.5 years for a typical Li-ion battery life). As outlined in the general calculations section above.

Economically, it is also a fairly cheap energy system to purchase in comparison to the other storage systems. In terms of scalability, the number of batteries is not ideal but it does not take up an inconvenient amount of space. However, the weight of the amount of batteries is an inhibiting factor to its other benefits.

Reliability

Overall, lithium-ion batteries are not that durable. They start degrading as soon as they leave the factory (at an infinitesimal rate) and have approximately a two to three year shelf life from manufacture date (7). This also factors into the cost consideration. Another aspect of the Li-ion battery is the fact that it can be recharged without completely running out. However, if the Li-ion battery ever does completely run out, it expires and cannot be reused. It is also very consistent and reliable. However, as stated, each battery will only last 2-3 years, so comparably to the other two storage options, it does not have a great durability.

ASRG

Energetic Storage and Performance

Elon Musk estimates 325 kW will be needed from an in-capsule battery to power the Hyperloop. Here, the ability of ASRG's to meet that need is considered. First, based on a recent NASA publication, each ASRG unit will produce approximately 130 W, implying:

325,000 W Needed* (1 ASRG Unit)/(130 W)=2,500 ASRG units

will be needed to supply a sufficient amount of power (20). This brings an immediate volume and weight concern. At 32 kg and 0.14 m^3 per unit, the battery system as a whole will weigh 80,000 kg and have a volume of 350 m^3 (20). Both are excessive in a capsule that is trying to minimize size to increase fuel efficiency.

From a thermodynamic point of view, NASA claims 26% efficiency (20). That is, 26% of the thermodynamic power of the ASRG is realized in the form of electric power (20). However, it is realized that the ASRG will be constantly producing energy on the basis of continuous radioactive decay, and so the team reduced this efficiency by a factor that considers a capsule's time offline. Further, by the nature of decaying fuel, the power will slowly diminish over the 14 years the battery is predicted to last (20).

In any case, from an energetic and performance point of view, ASRGs are certainly unusable for this application for the foreseeable future. It is noted that the technology is currently in the research and development phase, and that weight and space values are expected to reduce. Momentarily disregarding

the physical deficiencies of the ASRG, the safety, economics, and reliability is considered in the following sections.

Safety

The safety of ASRGs is an appealing aspect of this technology. The decay of Pu-238 is an alpha emitter. Unlike gamma particles, alpha particles can be blocked by a few centimeters of air or a thin piece of paper (21). Therefore, the exposure to humans is minimal to none. Moreover, the nuclear radioisotope used for fuel is in a ceramic form that would "break primarily into large, non- inhalable and non-soluble pieces, rather than fine particles that could be harmful to human health or the environment" (21). Clearly, the fuel itself is not the issue as at hand in regards to safety. In addition to being large and noticeable, the ceramic form of Pu-238 has a high melting point and low solubility in water, which implies that there is generally no release into the environment (21). This lowers the chance of contaminating rivers and lakes or polluting the fresh air. The fact that NASA has been safely using Pu-238 for space exploration for over 50 years is a testament to the safety of the ASRG technology (21). However, a main concern with the safety in this battery storage option is the excess heat produced from each ASRG needed.

Economics

Currently, ASRGs are being developed by NASA and the Department of Energy for space travel. By the nature of the project, it is a high cost venture and currently economically unfeasible for the Hyperloop. The main cost comes from the fuel Pu-238 at about $4,000 per gram (22). Needing 2500 kg of the fuel to provide the desired 325 kW, the cost comes to:

[U+3016]Cost[U+3017]_Fuel/Capsule ≈ 1 kg Pu/ASRG*2500 ASRGs/Capsule * $4,000,000/kg Pu = $10,000,000,000/Capsule.

However, knowing each battery will last for approximately 14 years, giving the time-normalized cost:

[U+3016]Cost[U+3017]_Fuel/(Capsule-Year)= ($10,000,000,000/Capsule)/14 Years≈$700,000,000/(Capsule-Year)

Assuming:

[U+3016] Cost[U+3017]_Pu≫[U+3016]Cost[U+3017]_Infrastructure

[U+3016]Cost[U+3017]_Total/(Capsule-Year)≈$700,000,000/(Capsule-Year)

So, in comparison to Elon Musk's prediction of a battery that costs around $150,000 per capsule, that the ASRG is not currently economically feasible. While this technology will likely not compete economically with lithium-ion batteries in the near future, let us consider an avenue through which money can be recouped.

First, the ASRG will be constantly producing 325 kW, even while not in use. Roughly assuming it is in use 25% of the time, selling back the electricity to California the remaining 75% of the time. At a price of around $0.15/kWh, there is a gain (23):

(325 kW)/Capsule* (.75*8765 hours)/Year* $0.15/kWh=$320,470/(Capsule-Year)

It is reasonable, though rough, to say this recouped money is on the order of the cost of infrastructure. Still, this refund is negligible to the cost of fuel and so it is required to consider ways the fuel might change price.

Note that the fuel PuO2 is currently out of production, contributing to its high cost. NASA currently has plans to produce the fuel again (24). If a market for PuO2 was created and similar to that for UO2 (certainly a non-sustainable assumption, but one that will be considered as large changes in the market), the prices would be similar (near $25 per gram) (25). This gives a much more reasonable fuel cost of:

[U+3016]Cost[U+3017]_Fuel/(Capsule-Year)= ($25/gram)/($4,000/gram)* $700,000,000/(Capsule-Year)= $4,375,000/(Capsule-Year)

This potential extreme change in cost in the long term would warrant reconsideration of the costs. However, recognizing the roughness of the estimates/comparisons and the lengthy time scale and maintain that the ASRG is not a feasible option economically for the Hyperloop.

Reliability

Reliability is an area where in which ASRGs excel. Since the fuel used to power these machines is Pu-238, the reliability of this element must be analyzed. One might think that using a decaying material as a fuel source would not be reliable nor give consistent results. However, this does not apply to Pu-238 because its half-life extends out to 88 years, which is past the lifespan of the ASRGs on average (21). Therefore, the

fuel source is reliable for the lifetime of an ASRG. Since this is a new technology and so far only NASA has done considerable research on it, extensive efforts are underway to evaluate, improve, and verify ASRG reliability even further. In the meantime, the NASA Jet Propulsion Laboratory has encouraged the use of ASRGs by using a defect detection and prevention risk (DDP) management tool (26). When looking at the reliability of ASRGs, an important aspect is the reliability of the Advanced Stirling Converters themselves. According to GRC, a member of the Lockheed Martin Space Systems Company, it is safe to say that the convertors for this technology have been continuously in long-term operations “alone or in pairs to simulate their configuration in generators” without any complications (26).

4 Conclusion

The LightSail technology is presented as an appropriate and safe candidate for an energy storage option for the Hyperloop. It provides the right amount of energy to power the capsule and it is the lowest cost of the three possible solutions. However, this is a highly theoretical technology therefore it is not as promising as the lithium-ion battery or the ASRG.

The ASRGs provide one of the safest alternatives because it uses a non-toxic source of fuel. The downside to this technology is the efficiency of the engine, which can be as low as 16 %. Additionally, although it is being funded by the Department of Energy for NASA’s use, the cost to use ASRGs to power the capsule is exorbitant.

The Lithium Ion battery has the highest score on the Pugh matrix. It scored especially high in the categories of Energy/Performance and Economics. It has excellent efficiency, feasibility, cost, and scalability. It also has great consistency and is very safe in terms of human health. It is a viable energy storage option for the Hyperloop system and is the most promising for use. Therefore, the Lithium Ion battery receives a full recommendation for the Hyperloop Transportation System.

5 Appendix

LightSail Calculations
Calculation 1

W=Power*time=(325 kJ/s)*(2100s)=682500 kJ = 682500000J

Calculation 2

V0=W/(Pa[1+(P0/Pa)[ln(P0/Pa)-1]]*e)

V0=(682500000 J)/(100[1+(2.0684E7/100)[ln(2.084E7/100)-1]]*0.70)

V0=4.19 m^3 = 4190 L

Li-Ion Calculations
Power=# batteries*efficiency*voltage*current

325 kW=(# batteries)(0.8992)(72 V)(100 Amps)

50.199 batteries=# batteries

Weight of battery=28 lbs

Volume of battery= 13" in x 6.75 in " x 8.87 in

1 battery system=51 batteries*28 lbs=1428 lbs

1428 lbs=647.73 kg

Volume of battery system=[(13 in)(6.75 in)(8.87 in)/(12in/ft)^3](51 batteries)= 22.97 [U+3016]ft[U+3017]^3

22.97 ft^3=0.650 m^3

51 batteries/capsule*$7,799.94/battery=$397,796.94

($397,796.94/capsule)/2.5 years for battery life=$159,118.66

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